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PHOTON CROSS SECTIONS AT ECM = 2 TEV

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Photon production rates have been studied by the DØ and CDF experiments in Run II of the Fermilab Tevatron Collider. Measurements of the inclusive isolated photon cross section and the di-photon cross section are presented, based on integrated luminosities of $0.3\,\text{fb}^{-1}$ and $0.2\,\text{fb}^{-1}$, respectively. The results are compared to perturbative QCD calculations in various approximations.

1 Introduction

Photon cross sections in hadron collisions receive contributions from "prompt" photons which directly emerge from the hard subprocess, and from photons which are produced during fragmentation. The latter are usually accompanied by hadrons, and their contribution can be significantly reduced by requiring the photon to be isolated from other particles in the event. Isolated photon cross sections are therefore dominated by prompt photons and are directly sensitive to the dynamics of the hard subprocess and to the strong coupling constant α_s and the parton density functions (PDFs) of the hadrons. Furthermore, di-photon final states are also signatures for various "new" physics processes, such as Large Extra Dimensions and for heavy new particles, such as the Higgs boson, decaying into photons.

Photon production has been considered an ideal source of direct information on the gluon density in the proton [1,2]. However, it was observed [3] that not all experimental data are consistently described by perturbative QCD (pQCD) calculations in fixed order of the strong coupling constant, α_s. On one hand, it was argued that the existing data may not be consistent [3]. It was also suggested that the phenomenological introduction of intrinsic transverse momentum of the incoming partons may help improve the description of the data and reduce the inconsistencies [4]. But this ad-hoc procedure still had a significant model dependence and was not seen to be a fundamental solution. In recent global PDF fits photon data have been excluded [5,6].

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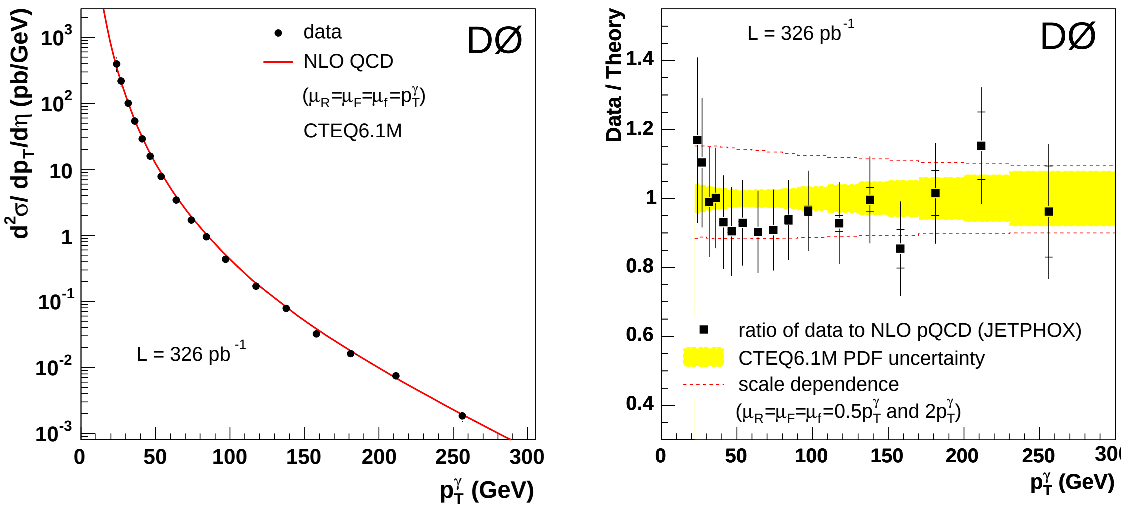

Figure 1: The isolated photon cross section as a function of the transverse photon momentum p_T (left) and the ratio of data and the NLO pQCD calculation from JETPHOX (right).

In order to rescue the photon data as a source of additional information on the PDFs, it is important either to identify critical missing pieces in theory or to clearly establish inconsistencies of existing data sets. Precision measurements in new kinematic regions are vital for testing theory predictions. In this article, we present recent results from the DØ and the CDF experiments on the inclusive isolated photon cross section and the di-photon cross section, measured in proton-antiproton collisions at a center-of-mass energy of $\sqrt{s} = 1.96\,\mathrm{TeV}$ during Run IIa of the Fermilab Tevatron Collider.

2 Isolated Photon Cross Section

At lowest order, prompt photons are produced via quark-gluon Compton scattering or quark-antiquark annihilation. Additional contributions to the inclusive photon cross section stem from the fragmentation of energetic π^0 and η mesons. In the DØ analysis [7], photon candidates are defined as clusters of electromagnetic calorimeter cells within a cone of radius $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.2$, if more than 95% of the energy is deposited in the electromagnetic part of the calorimeter and the probability of a matching track is below 0.1%. Cosmic backgrounds and electrons from W decays are removed by requiring that the missing transverse energy in the event is less than 70% of the transverse photon momentum (p_T). Photons with $p_T > 23\,\mathrm{GeV}$ are selected in the range of pseudorapidities $|\eta| < 0.9$. The isolation criterion requires that the energy in a cone of radius $\Delta R < 0.4$ not associated with the photon is less than 10% of the photon energy. The main background in the measurement are hadronic jets with a large electromagnetic fraction. A neural net is trained to discriminate between photons and background using four sensitive variables [7]. The photon purity was determined as a function of p_T by fitting the neural net output for Monte Carlo signal and background to the observed distribution of photon candidates. The photon p_T distribution is corrected for energy resolution in an iterative unsmearing procedure. The largest contributions to the experimental uncertainty are due to the purity determination and the photon energy calibration.

The results are based on 2.7 million photon candidates in an event sample corresponding to an integrated luminosity of $L_{\mathrm{int}} \simeq 0.3\,\mathrm{fb}^{-1}$. The isolated photon cross section is shown in Fig. 1 (left). The cross section falls over five orders of magnitude in $23 < p_T < 300\,\mathrm{GeV}$, the widest p_T range ever covered by a single experiment. The pQCD predictions are computed in next-

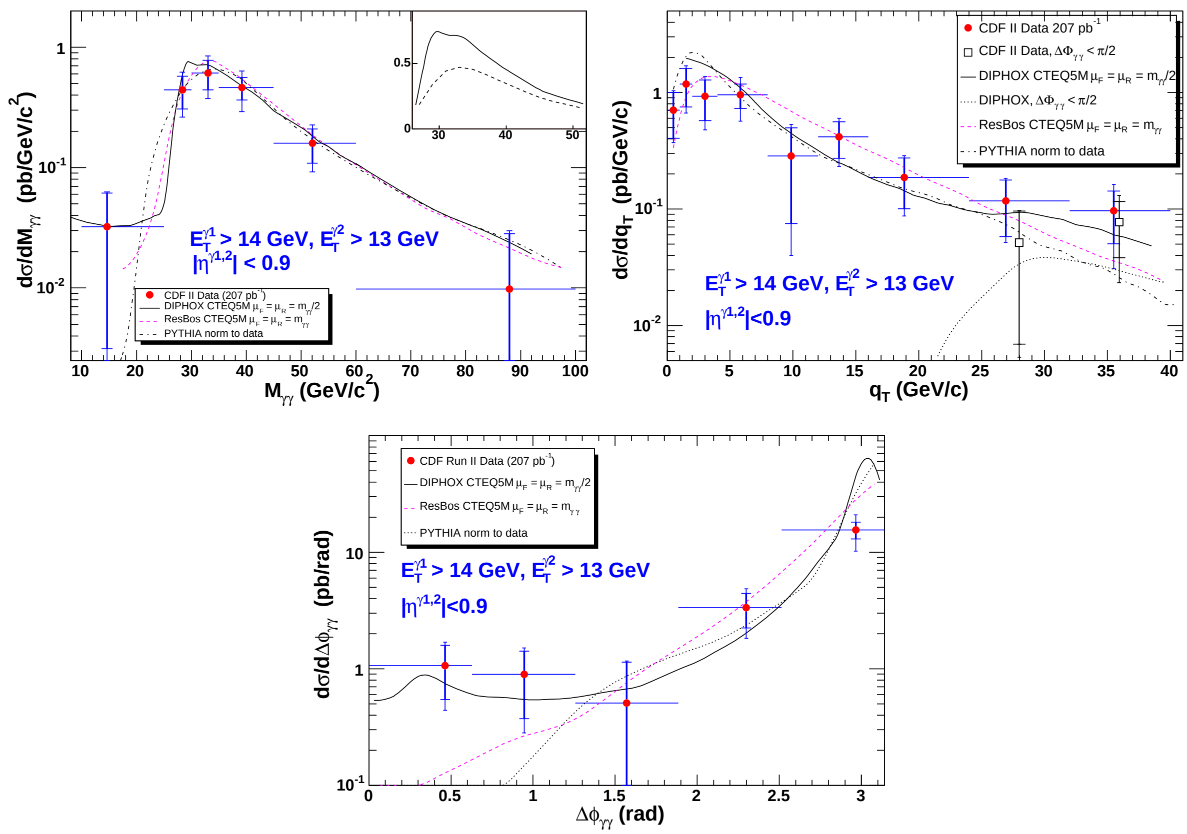

Figure 2: The CDF measurement of the di-photon cross section as a function of the di-photon mass $M_{\gamma\gamma}$, the vector-sum of the transverse photon momenta q_T, and the difference in azimuthal angle $\Delta\phi_{\gamma\gamma}$.

to-leading order (NLO) in α_s using the program JETPHOX [8,9] with CTEQ6.1M PDFs [6], BFG fragmentation functions [10], and renormalization, factorization and fragmentation scales set to $\mu_{R,F,f} = p_T$. The ratio of data and theory is shown in Fig. 1 (right), and it is obvious that NLO theory gives a good description of the data over the whole p_T range. The scale dependence of the NLO calculation is of the same size as the experimental uncertainties. Uncertainties from the proton PDFs are significantly smaller over most of the p_T range. PDF sensitivity can therefore only be achieved if both experimental and theoretical uncertainties can be significantly reduced.

3 Di-Photon Cross Section

The leading contributions to di-photon production are from quark-antiquark annihilation and from gluon-gluon-scattering. Although the latter process is suppressed by a factor of α_s^2 (as the photons couple to a quark box), its contribution is still significant at small di-photon masses. In this kinematic range the PDFs are probed at small momentum fractions, where the gluon density is much larger than the quark densities. In addition to the prompt contributions, the di-photon cross section also receives contributions where one or two photons are produced in fragmentation processes. The CDF analysis [11] selects photon candidates based on the lateral shower profile and a veto against a matching track. The isolation criterion requires the transverse energy in a cone radius of $R = 0.4$ around the photon direction, not associated with the photon, to be below 1 GeV. In total 427 ± 59 (stat.) di-photon events in 889 di-photon candidates are selected in the data sample corresponding to $L_{\rm int} \simeq 0.2\,{\rm fb}^{-1}$.

The di-photon cross section is presented in Fig. 2 as a function of di-photon mass (top left), the di-photon transverse momentum q_T (top right), and the difference in azimuthal angle $\Delta\phi_{\gamma\gamma}$

between the two photons (bottom). The results are compared to different approximations of pQCD. The program DIPHOX [8] includes NLO matrixelements for both the direct contribution and the fragmentation contribution, and the $\mathcal{O}(\alpha_s^3)$ corrections [12] to $gg \to \gamma\gamma$ have been added here to the calculation. The program ResBos [13] has implemented the fragmentation contributions only at LO but it includes resummation of soft initial-state gluon radiation. Also shown are the results for PYTHIA [14] (LO matrixelements plus parton shower and fragmentation model) which have been scaled by a factor of two. All calculations give a reasonable overall description of the data, except in specific "critical kinematic regions" in which the unique features of the different calculations are probed. The contributions from fragmentation processes are especially large in the regions of small di-photon masses, large q_T, and small $\Delta\phi_{\gamma\gamma}$. These regions are only described by DIPHOX which includes the NLO corrections for the fragmentation process. The q_T and the $\Delta\phi_{\gamma\gamma}$ distributions are directly sensitive to higher-order effects, since in lowest order both are trivial ($q_T = 0$, $\Delta\phi_{\gamma\gamma} = \pi$). The kinematic regions at low q_T and large $\Delta\phi_{\gamma\gamma}$ are especially sensitive to soft initial-state gluon emissions. Only ResBos describes this phase space due to the resummation of initial-state gluon radiation effects. PYTHIA is not only too low by a factor of two, but it also fails in all "critical regions". For an overall description of di-photon production a full NLO calculation (for direct and fragmentation contributions), combined with $\mathcal{O}(\alpha_s^3)$ $gg \to \gamma\gamma$ corrections plus resummed initial-state contributions would be required.

4 Summary

The CDF and DØ experiments have published the first measurements of the single inclusive photon cross section and the di-photon cross section at a center-of-mass energy of $\sqrt{s} = 1.96\,\mathrm{TeV}$. The new inclusive isolated photon data extend previous measurements and indicate that the $\sqrt{s}$ and the p_T dependence of direct photon production can be adequately described in NLO accuracy [15]. In the future, PDF sensitivity can only be achieved, if both experimental and theoretical uncertainties can be significantly reduced. The di-photon mass, q_T and $\Delta\phi_{\gamma\gamma}$ dependence of the di-photon cross section can not be simultaneously described by a single existing theory calculation. In different regions of phase space, different contributions are required: full NLO accuracy, in the direct and the fragmentation contributions, resummed initial-state contributions and the $\mathcal{O}(\alpha_s^3)$ corrections to $gg \to \gamma\gamma$. Since all the single ingredients are available, it should not be difficult to combine these into a powerful di-photon prediction.

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